

QinetiQ Studies on Wear and Erosion in Gun Barrels

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SUMMARY

QinetiQ is conducting research into the wear and erosion of indirect fire guns under contract from the United Kingdom Ministry of Defence. The objectives of the work are to improve the UK's understanding of the causes and mechanisms of wear and erosion in gun barrels, and to investigate means by which the wear and erosion may be reduced, thereby extending the life of the gun barrels. Key to this work is the development of computational models that can predict the wear and erosion in a gun system, comprising a barrel, charge and projectile. The work is applicable also to direct fire guns, cannons and mortars. This paper describes experimental and theoretical studies that have been undertaken to investigate wear and erosion in conventional uncoated steel barrels.

1.0 INTRODUCTION

Wear and erosion was probably first identified as a significant problem for guns in 1886 when Abel stated "The great increase which has been taking place during the last 25 years in the power of artillery has brought the subject of erosion of gun barrels into prominence, and it is not too much to say that it now forms one of the chief difficulties to be encountered by the makers of a heavy gun. As far as can be seen at present, its sufficient mitigation is the one great difficulty, which seems likely to impose a limit on the size and power of ordnance in future" [1]. This statement is largely still valid today. Although much progress has been made towards understanding the causes of wear in gun barrels, and means have been proven for reducing the wear and extending the barrel life, it is still a significant problem for most types of gun.

An excellent introduction to wear and erosion in gun barrels is contained in [2]-[4]. The major contributors to wear and erosion of gun barrels are usually grouped under the headings: thermal factors, chemical factors and mechanical factors. The relative contributions of these factors vary from system to system. Generally, however, thermal and chemical effects are considered to be the dominant factors.

When a gun is fired the barrel wall is subjected to heating by a hot gas, typically 3000K and at 400MPa, for up to 20ms. This barrel heating leads to softening, thermal phase transformation and melting of the bore surface. Considerable thermal heating, due to forced convection, can be caused by gas wash between the projectile driving band and the bore surface.

The main constituents of propellant gases are CO, CO₂, H₂, H₂O and N₂. Minor components will include NH₃, CH₄, NO, free radicals and ions. Gun propellants are formulated to be oxygen deficient so their combustion products are reducing in nature. These gases react at the bore surface. Carbon and nitrogen diffuse into the barrel, softening the bore surface. The conditions lead to a phase transformation of the gun steel; above 750°C the austenite, or gamma, phase is formed. Further carbon penetration reduces the melting point of the austenite. As the austenite cools, it transforms to a martensite phase. Cracks form,

Paper presented at the RTO AVT Specialists' Meeting on "The Control and Reduction of Wear in Military Platforms", held in Williamsburg, USA, 7-9 June 2003, and published in RTO-MP-AVT-109.

| Report Documentation Page | | | | Form Approved OMB No. 0704-0188 | |
|--|------------------------------------|-------------------------------------|---|--|---------------------------------|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. | | | | | |
| 1. REPORT DATE 01 JUN 2004 | | 2. REPORT TYPE N/A | | 3. DATES COVERED - | |
| 4. TITLE AND SUBTITLE QinetiQ Studies on Wear and Erosion in Gun Barrels | | | | 5a. CONTRACT NUMBER | |
| | | | | 5b. GRANT NUMBER | |
| | | | | 5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S) | | | | 5d. PROJECT NUMBER | |
| | | | | 5e. TASK NUMBER | |
| | | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) QinetiQ MOD Fort Halstead, Sevenoaks Kent TN14 7BP United Kingdom | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited | | | | | |
| 13. SUPPLEMENTARY NOTES See also ADM201869, RTO-MP-AVT-109 The Control and Reduction of Wear in Military Platforms (Contrôle et réduction de l'usure des plates-formes militaires)., The original document contains color images. | | | | | |
| 14. ABSTRACT | | | | | |
| 15. SUBJECT TERMS | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT UU | 18. NUMBER OF PAGES 12 | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT unclassified | b. ABSTRACT unclassified | c. THIS PAGE unclassified | | | |

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further degrading the quality of the bore surface. Cementite (FE₃C) is also formed at the surface, further promoting softening and cracking.

Mechanical contributions to wear arise from the propellant gases and the projectile. Unburned propellant and small solid particles from the primer, and other sources, are entrained in the high velocity gas flow and have an abrasive effect on the bore surface. For a rifled barrel, mechanical wear arises from the engraving of the driving band into the lands and grooves at the commencement of rifling. This process causes considerable stress on the gun barrel. The spinning of the projectile, as it travels along the barrel, causes further mechanical wear. For rifled and smoothbore barrels the radial pressure between the driving band and the bore produces friction and an abrasive action on the bore surface.

Most wear occurs around the commencement of rifling (or the end of the forcing cone for smoothbore barrels). However, significant wear can occur at the muzzle end due mainly to the projectile motion but also due to particulate abrasion. Ways to mitigate wear and erosion in gun barrels include liners, chromium plating, ablators, wear-reducing additives to the propellant and low flame temperature propellants.

Militaristically, the main effect of wear and erosion is reduced muzzle velocity, resulting in loss of range and accuracy. The wear life of a barrel can vary from 100-200 rounds for a tank gun to several thousand rounds for an artillery gun. However, increasingly there are demands for substantial increases in muzzle velocity for existing and new gun systems, creating considerable challenges to wear and erosion mitigation techniques. Understanding the causes of wear and erosion, and being able to reduce their effects, is vital to the success of future gun upgrades and new gun systems.

The Royal Armament Research and Development Establishment (RARDE, now QinetiQ), Lawton and CHAM (under contract from RARDE) carried out previous work on wear and erosion in the UK in the 1980s [5], [6]. Lawton continued work at a low level in the 1990s [7]. Reference [5] reported on techniques to measure wear in a medium calibre gun. Firings of experimental propellants having different flame temperatures showed that barrel wear was not a function of flame temperature alone; chemical effects played a significant role. CHAM used their Phoenix code to simulate the effect of additives, such as talcum powder which was impregnated in combustible cartridge cases, on the wear and erosion of 120mm tank guns. This work was not totally successful, as the model did not predict the reduction in heat transfer for additives that had been measured. Lawton's work consisted of measurements of heat transfer in gun barrels and the development of semi-empirical equations relating the wear rate to flame temperature and gas species concentrations.

UK government research on wear and erosion concentrated on coating techniques in the late 1980s and 1990s. It was not until about 1998 that research into the causes of wear and erosion was restarted in the Defence Evaluation and Research Agency (DERA, now QinetiQ). This research programme was funded at a low level and so it was decided to concentrate firstly on thermal heating contributions to wear and erosion. Chemical factors and then mechanical factors would be considered later. Furthermore, the research would concentrate, initially, on uncoated steel barrels.

The initial approach taken was to conduct vented vessel firings of a nitramine propellant. Pressures and temperatures were measured. Modelling of these firings was conducted using a one-dimensional (1D) internal ballistics code. This paper describes the experimental work conducted, details of the modelling and future experiments using an improved design of the test vessel.

2.0 VENTED VESSEL FIRINGS

These firings were conducted in support of collaborative work for a Technical Co-operation Program on wear and erosion in gun barrels. The propellant used consisted of RDX (76%) in a binder composed of

cellulose acetate butyrate, BDNPA/F and nitrocellulose. The flame temperature of the propellant was 3007K and its impetus was 1.16MJ/kg. The propellant was in the form of 19-hole cylindrical grains, 7.3mm diameter, 11.1mm long and with a perforation diameter of 0.3mm.

The vented vessel firings were conducted using a replaceable steel section sample adjacent to the vessel containing the burning propellant. Weighing the sample before and after firings enabled the eroded mass loss to be calculated. Figure 1 shows the sample in its holder assembly. The sample, on the left-hand side (the combustion vessel is further to the left but not shown), had two MEDTHERM K-type eroding thermocouples inserted. The burst disc allowed the pressure to build up to a specified value, helping to ensure good propellant combustion, before venting to the open-air occurred, through the nozzle. The volume of the combustion vessel was 700cc. The gas pressure was measured in the combustion vessel using a Kistler gauge.

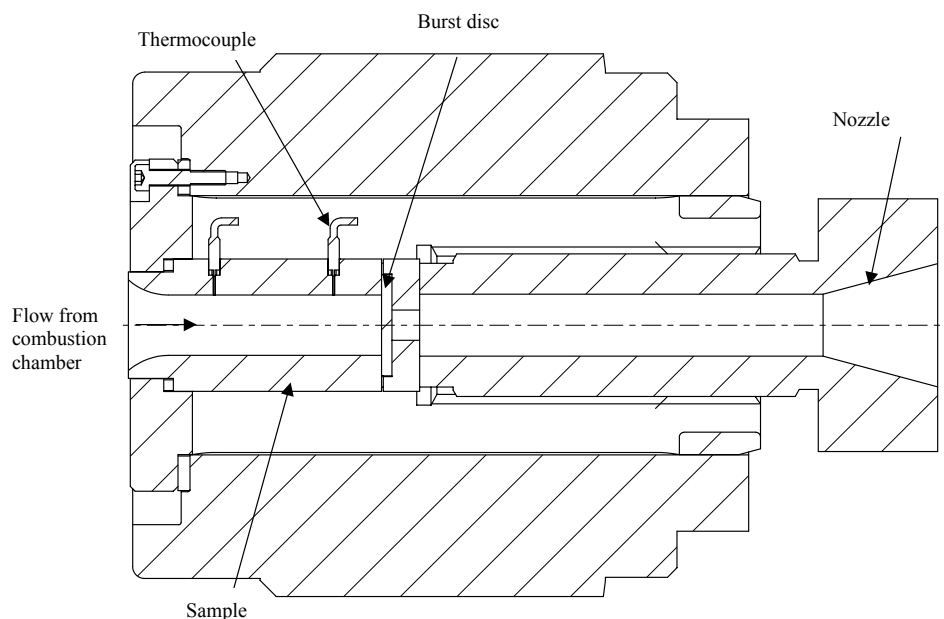


Figure 1: Sample in holder assembly.

The thermal properties of the thermocouples are different from those of gun steel. Table 1 compares these data. These differences mean that the thermocouple will record temperatures that are about 10% greater than those of gun steel.

Table 1: Thermal Properties of Thermocouples and Gun Steel

| Thermal property | Thermocouple | Gun steel |
|---------------------------------|--------------|-----------|
| Conductivity (W/m/K) | 24 | 35 |
| Diffusivity (m ² /s) | 7.3E-6 | 9.1E-6 |

Each vented vessel firing used up to 250g of propellant, attaining a maximum pressure of 320MPa. Figure 2 compares the measured pressures for a series of five rounds fired under similar conditions. The variability in the pressure profiles was attributed to the bursting process (the burst pressure was nominally 90MPa). Also shown in Figure 2 is the predicted pressure profile using a 1D internal ballistics code named CTA1, which is described in section 3.0.

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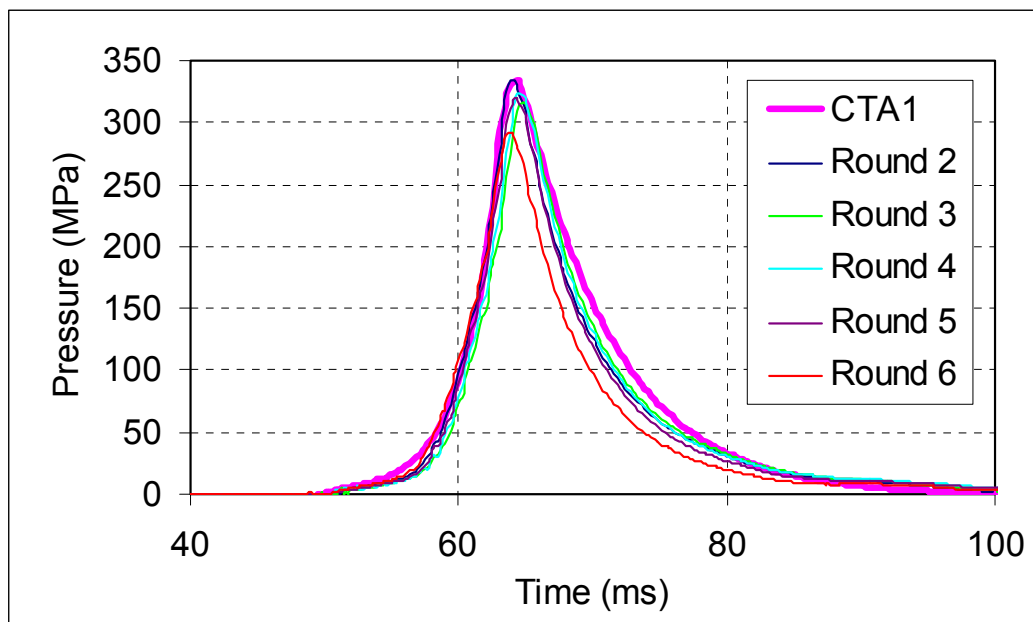


Figure 2.

Figure 3 compares the measured temperature profiles for the same firings - the temperatures have not been adjusted to account for the difference in thermal properties between the thermocouple and the gun steel. Not all rounds gave good thermocouple recordings. The curves labelled 'T1' were recorded by the thermocouple nearer to the combustion chamber. There is considerable round-to-round variability in the measured temperatures. The cause of this variability is unknown and is being investigated. Variability in temperature measurements has also been reported by other workers [9].

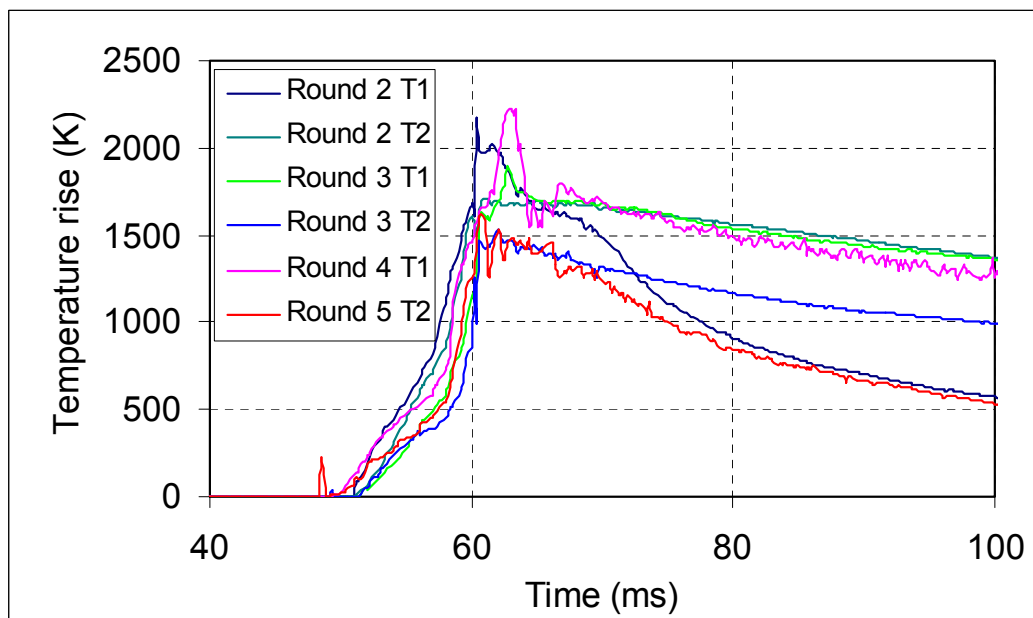


Figure 3: Vented vessel temperature-time histories.

3.0 MODELLING

3.1 CTA1 Code

The CTA1 code [10] is a quasi-1D, multi-phase flow model of the internal ballistics of various types of gun. It allows for area changes along the barrel provided they are small. It includes submodels for interphase drag, intergranular stresses, heat transfer to the barrel walls, propellant ignition and engraving/sliding/air resistance. Numerous different propellant geometries can be simulated, including multi-perforated cylindrical and hexagonal grains, large diameter disc propellant and layered/deterred propellants. The burning surface area of the grains is calculated exactly to take slivering into account. The implementation of a secondary chamber allows the code to model primers, fume extractors, mortars and special cased telescoped ammunition concepts. Gas leakage effects (e.g. past the projectile driving band or from the breech) are included in the model.

The CTA1 code has been extensively validated and applied to closed vessels, vented vessels, cased telescoped ammunition concepts, mortars, conventional guns and electrothermal-chemical (ETC) guns.

3.2 Heat Transfer Model

The barrel wall is treated as a semi-infinite flat plate. Barrel curvature and heat diffusion along the length of the barrel are both neglected because the penetration depth of heat in any firing will be small.

The heat conduction equation that needs to be solved, including ablation at the surface, is

$$\rho c \frac{\partial T}{\partial t} + \rho v \frac{\partial T}{\partial x} = \lambda \frac{\partial^2 T}{\partial x^2} \quad (1)$$

with the boundary condition

$$q_c + q_r = -\lambda \left. \frac{\partial T}{\partial x} \right|_{x=0} + \rho v L \quad (2)$$

where ρ is the density of the barrel, c is the specific heat capacity of the barrel, v is the ablation rate of the barrel surface, T is the barrel temperature, t is time, λ is the thermal conductivity, x is the distance into the barrel from the surface, q_r is the radiative heat flux, q_c is the convective heat flux and L is representative of an endothermic energy sink (e.g. latent heat).

The radiative heat flux is given by

$$q_r = \epsilon_w \sigma_{SB} (T_g^4 - T_0^4) \quad (3)$$

where ϵ_w is the emissivity of the barrel wall, σ_{SB} is the Stefan-Boltzmann constant, T_g is the gas temperature and T_0 is the barrel surface temperature. A value of 0.7 was used for the barrel emissivity in the calculations presented in this paper.

The calculation of the convective heat flux follows the method described in [11]. A fully turbulent boundary layer is assumed. The skin friction is calculated from the boundary layer equations. Reynolds' analogy, with the extension due to von Karman, between the transfer of momentum and heat in turbulent flow is assumed to hold. The von Karman extension applies when the Prandtl number, Pr , is not equal to unity. The convective heat flux is given by

$$q_c = \rho c u / [a \eta^{1/n} F(Pr)] \quad (4)$$

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where u is the gas velocity, a and n are constants and η and $F(\text{Pr})$ are given by the equations

$$F(\text{Pr}) = a\eta^{1/n} + 5[(\text{Pr}-1) + \log(1 + 0.83(\text{Pr}-1))] \quad (5)$$

$$\eta = (5\text{Re}/a^3)^{n/(n+3)} \quad (6)$$

Re is the Reynolds number and is given by

$$\text{Re} = u x \rho / \mu \quad (7)$$

where μ is the gas viscosity which is calculated from the Sutherland equation

$$\mu = 1.458 \times 10^{-6} T_g^{1.5} / (T_g + 110.33) \quad (8)$$

Finally

$$\text{Pr} = 4\gamma / (9\gamma - 5) \quad (9)$$

where γ is the ratio of specific heats for the gas. The parameters a and n were chosen so that the skin friction derived by the power law should be a good approximation to experimental data for Reynolds numbers in the range 10^5 - 10^{10} and are

$$a = 12.4; \quad n = 11.3 \quad (10)$$

This barrel heating and ablation model has been validated for gun firings by comparing its predicted temperatures with those obtained from 155mm ETC gun firings. Figure 4 shows a typical comparison for a firing of zone 1 of an experimental modular charge system. The measured temperatures have been adjusted downwards by 10% to take into account the different thermal properties of the thermocouples and the gun steel. Also compared in Figure 4 are the measured and predicted pressure profiles. The predicted and measured pressures are in excellent agreement. The predicted temperatures are in good agreement with those measured, though the peak temperature rise is nearly 10% less than that measured. For this firing, the thermocouple was located forward of the rear of the driving band, so that it would not be exposed to the propellant gases until the projectile had travelled 20cm. Although the measured temperature profile rises about 2ms before that predicted, this is probably due to the projectile engraving resistance profile used in the simulation.

3.3 Modelling of Vented Vessel Firings

These were modelled using the CTA1 code. This presented some difficulties due to the large change in cross-sectional area between the combustion chamber and the steel sample. The diameter of the combustion chamber was 76mm whereas the internal diameter of the sample was 13mm, which opened up to 19mm at the entrance to the combustion chamber. The CTA1 code can not deal with sudden changes in cross-sectional area. Therefore the transition between the combustion chamber and the steel sample was smoothed out over 8mm. To avoid transgressing the CTA1 model assumption of small variations in cross-sectional area, this smoothing necessitated a large number of cells to resolve adequately the area change. Four hundred cells were used to represent the region between the burst disc and the opposite end of the combustion chamber, a distance of 20cm, which was equivalent to a cell length of 0.5mm. Over the transition region, the change in diameter per cell was 4mm, which is still rather large. However, simulations conducted with finer mesh resolutions indicated that four hundred cells were sufficient, using a greater number did not significantly affect the results.

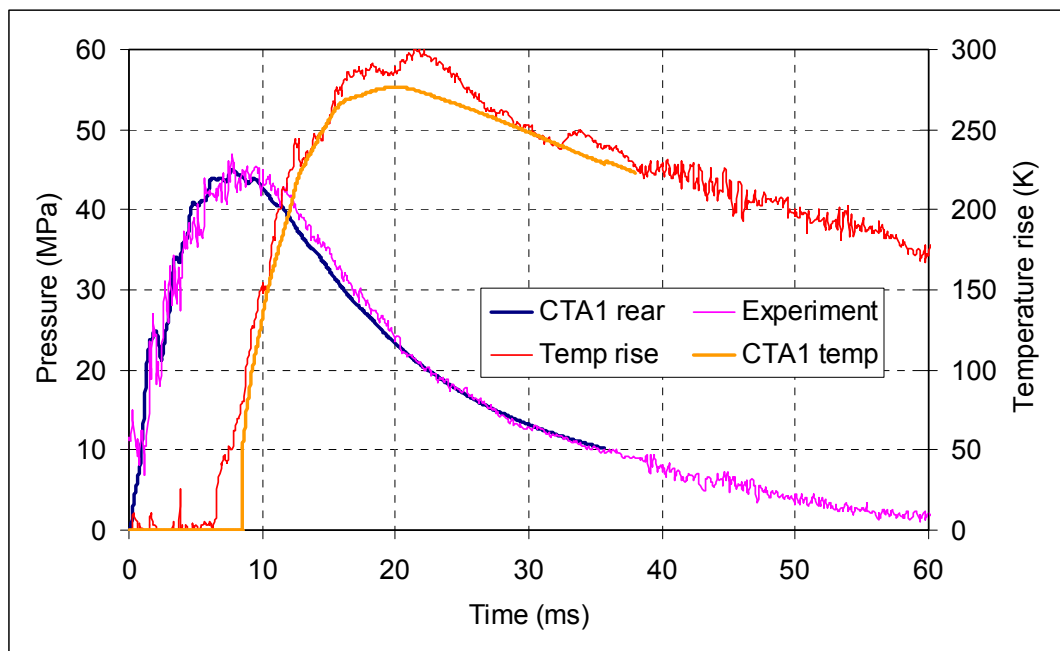


Figure 4: Comparison of predicted and measured profiles for 155mm ETC gun firing.

Axial distributions of pressure, temperature, gas velocity and total heat transfer coefficient were plotted to determine the effect of the chamber-sample profiling on the predictions. Figure 5 shows the distributions at intervals of 1ms just after the disc burst. The thermocouple positions were at 0.171m and 0.196m. The curves at different times indicate that both gauge positions were just within a region in which there are small spatial gradients in the predicted parameters. Therefore it was concluded that the chamber-sample profiling used did not adversely affect the predictions.

Figure 6 compares the predicted and measured temperatures at the thermocouple positions, not correcting the measured temperatures to account for the differences in thermal properties. A first impression would lead to the conclusion that the comparison is very poor. The predicted temperature rose 10ms after the measured profile and rose to a peak value about 300K lower than those recorded. During the temperature rise period, the predicted temperatures were over 500K lower than those measured. However, a review of the barrel heating model revealed that there was no conductive component for the heat transfer process between the gas and the barrel, only radiative and convective components. Before the burst disc ruptures, the gas velocities in the combustion chamber and sample will be low, so the convective heating component will be small. Heat conduction is the dominant heating mechanism until the disc bursts. Figure 7 compares the predicted and measured temperatures when the conductive heating component is included. There is much improved agreement. Although the predicted maximum temperature occurs at a later time than those measured, this is attributed to the venting process. The disc bursting will occur more gradually and may occur earlier than assumed in the modelling.

The measured mass losses from the steel samples were in the range 2.0-2.6g (mean of 2.2g). The predicted ablated mass loss was 1.5g, which is 30% lower than the average of those measured. However, the current model takes into account only thermal contributions to wear and erosion.

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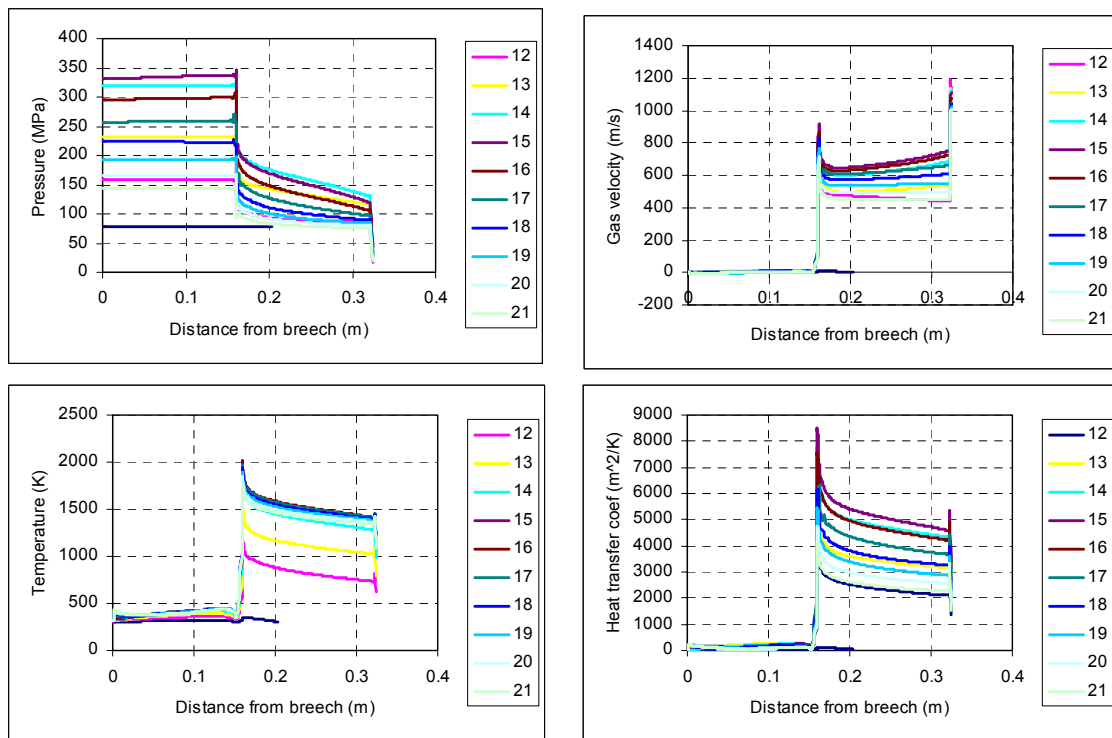


Figure 5: Predicted axial distributions after disc burst.

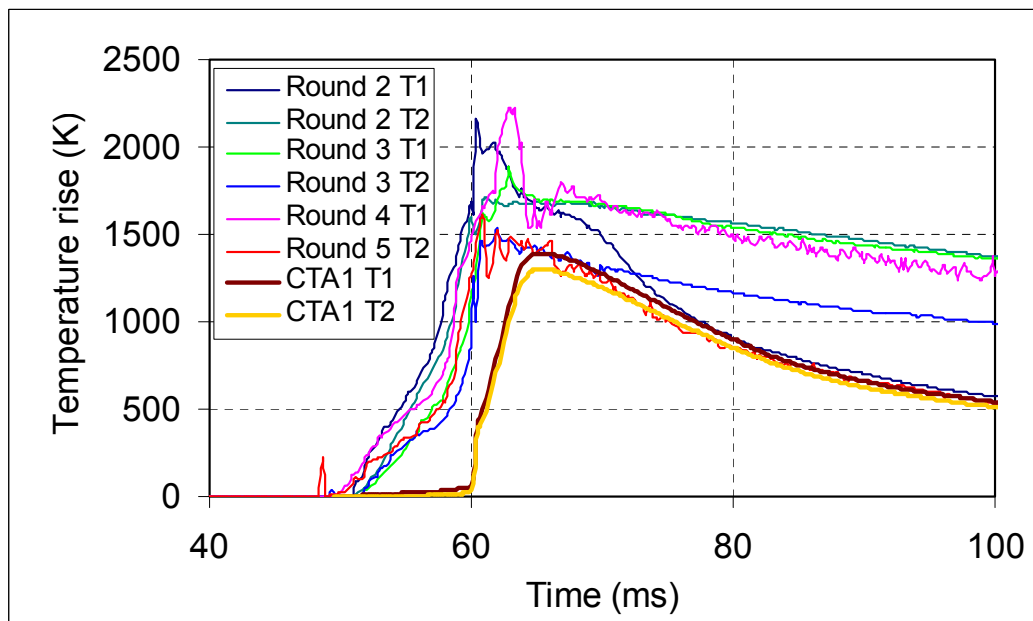


Figure 6: Comparison of predicted and measured temperatures.

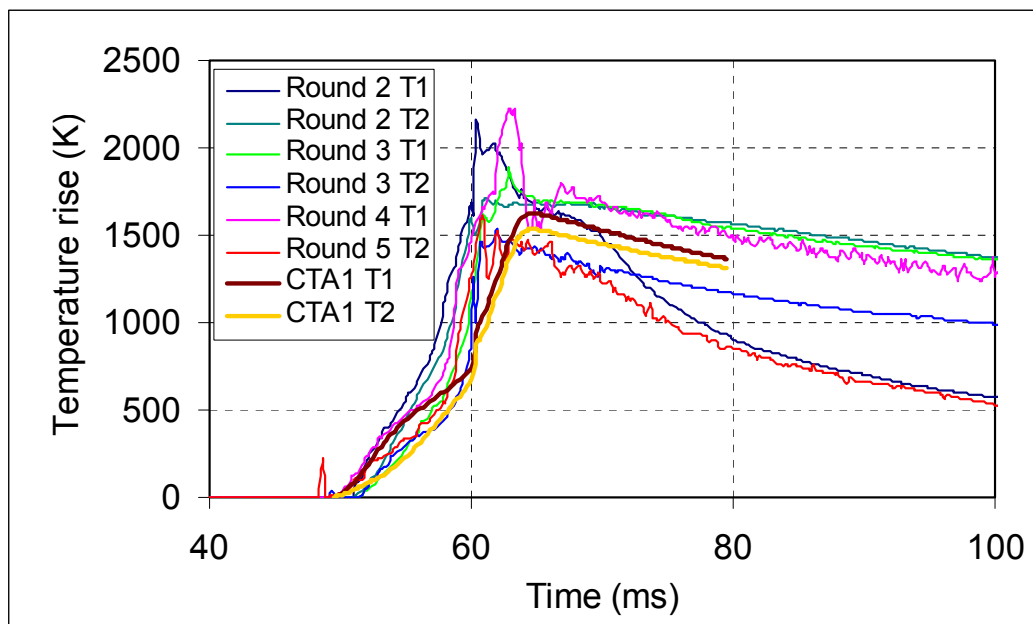


Figure 7: Predicted temperatures including conductive heating component.

4.0 IMPROVED VESSEL

Although vented vessel fixtures have been used throughout the world to investigate wear and erosion of different propellants and materials, there have always been concerns that it may not simulate very well the conditions in a gun. The empirical heat transfer correlations may not be valid for some firing conditions. Reference [12] reports work conducted by SNPE using a vented vessel fixture. This work shows fair agreement between predicted and measured eroded masses for loading densities of 0.12g/cc. However, for a higher loading density (0.19g/cc) the agreement becomes considerably worse. Furthermore, for a particular LOVA propellant, with a flame temperature of 2600K, the predicted mass loss is 40% of that measured. As the SNPE model includes heating, ablation and chemical effects, there appears to be some important chemical reactions missing from the model or there could be considerable abrasion due to particulate matter in the combustion products. For comparison, the loading density used in the QinetiQ vented vessel was 0.35g/cc, considerably higher than those used in the SNPE fixture.

Therefore it was decided to improve the design of the vented vessel fixture by making it more like a gun. Figure 8 shows the new design. The combustion chamber (not shown) interfaces with the left-hand side of the fixture. The sample, instrumented with two thermocouples, is shown on the left of the fixture. Instead of a burst disc, a 20mm barrel is attached to the end of the sample. A 250g projectile (not shown) is located in the region of the sample-barrel interface. A third thermocouple is located halfway along the barrel. Pressure gauges (not shown) are located in the barrel, one opposite the third thermocouple and the other near the sample. As with the first design, the combustion chamber pressure will also be measured.

Future work will include comparing the erosive effects of different propellants and different materials. Particular emphasis will be placed on getting more consistent thermocouple measurements. Modelling of these firings will be conducted to provide further validation of the computer model. The effects of using different convective heating correlations will be investigated. Funds permitting, the heating/erosion model will be enhanced by including the effects of chemical reactions.

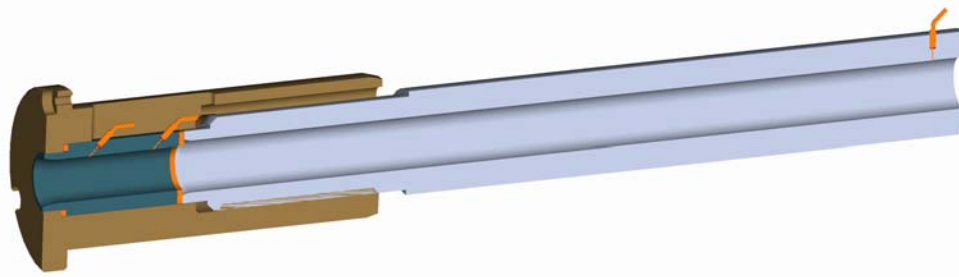


Figure 8: Improved erosion fixture.

5.0 CONCLUSIONS

Firings of a vented vessel erosion fixture have been conducted and show good consistency for the measured pressures. However, the measured temperature profiles show wide variations. The causes of these variations will be investigated in future work.

A barrel heating and ablation model has been implemented in the CTA1 internal ballistics code. This model has been validated using results from 155mm ETC gun firings and vented vessel firings.

Simulations of the vented vessel firings showed the importance of including the conductive heating component. When this effect was included in the model, good agreement between predicted and measured temperatures was obtained.

Concerns that the vented vessel fixture may not produce conditions representative of those achieved in gun firings led an improved vented vessel design to make it more like a gun. This improved design will be used to compare the erosivity of different propellants and samples. Data from these firings will be used to validate the barrel heating and ablation model further, and to form a database of propellants/materials/erosivity.

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QinetiQ Studies on Wear and Erosion in Gun Barrels

AVT-109**Specialist Meeting on the Control and Reduction of Wear in Military Platforms****Summary of Discussion Sessions**

The following presents a summary of the discussion of papers presented in the various sessions of the workshop. Only questions where the authors provided transcripts of their answers are reported.

Session 3 – Modelling of Wear and Erosion

Chair: Dr. Daniel Chaumette, Dassault Aviation, France

Paper MP-AVT-109-15

Dr. D. Chaumette, France,

Q. In your paper you presented temperature profiles measured in your test apparatus. How about the effect of flow speed, particularly considering the presence of solid particles?

Dr. Clive Woodley, Qinetiq, UK.

A. The gas velocity effects are included in the calculation of the convective heating coefficient. As far as solid particles are concerned, then they will have an abrasion effect but its relative contribution compared with gas convective heating has not been measured.